Assessing the Lagrangian Predictive Ability of Navy Ocean Models

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LONG-TERM GOALS

We are interested in understanding energetic processes at sub-mesoscales and mesoscales that drive ocean transport throughout the water column. Understanding and modeling these processes remains a significant challenge for oceanographers because their evolution is typically nonlinear and they are often driven by forcing mechanisms that can be both brief and episodic.

OBJECTIVES

With prior ONR support, we have developed and applied a variety of Lagrangian analysis tools to archived ocean model velocities to learn more about how submesoscale and mesoscale dynamics influence ocean transport. In many regions, Lagrangian analysis of model forecasts reveals a rich variety of evolving mixing boundaries (often called Lagrangian coherent structures or LCS) with intricate spatial structure at both large and small scales. As model resolution increases, more and more small-scale details emerge in model forecast LCS maps. Since these maps rely on thousands of modeled trajectories, their usefulness depends on ocean models with demonstrated Lagrangian forecast skill. Our objective is to assess this skill using a number of Navy ocean models in different geographic regions. LCS maps are extremely difficult to benchmark with observations, since detecting and tracking them likely requires thousands of drifters. Instead, we pursue a more manageable objective: quantifying Navy ocean model trajectory forecast skill over one forecast cycle (typically 72 hours) by comparing predicted trajectories with those from small groups of real drifters.

APPROACH

Our Lagrangian analysis approach relies on computing large numbers of trajectories directly from archives of ocean model velocities. The trajectories can be compared with observations, for model assessment, or can be used to compute synoptic maps showing the spatial distribution of Lagrangian properties. LCS maps are one example.

Model trajectories are computed at one model depth, using path equations that describe simple 2D advection in the horizontal. Linear interpolation of model velocities in both space and time is used.

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The path equations are integrated using a Runge-Kutta scheme with adaptive time-stepping. For the analysis here we make no attempt to include the effects of vertical motion, velocity uncertainties, or processes at scales below the model grid resolution. Also, no corrections are applied to account for wind slip of the observed drifters.

To assess Lagrangian forecast skill, we define a metric, *separation after three days*, the distance between an observed and modeled trajectory (in km) after a three-day period. We have explored other metrics, but they will not be discussed here.

During this performance period, we used small groups of observed trajectories for drifters launched as part of four Navy acoustics experiments (FAST-04, LWAD-05, LWAD-06, and LWAD-07) during the period 2004 through 2007. To increase the sample size, observed trajectories were divided into three-day segments with “launch” times chosen as 0000 UT daily. Although these segments overlap in time, each launch is treated as an independent event. These observed trajectory segments were used to assess the Lagrangian predictive skill of the Navy EAS16 model. In addition, drifters from the LWAD-07 experiment (with “launches” separated by three days, to eliminate their overlap in time) were used to assess the Lagrangian predictive skill of twenty-four RELO model ensemble members.

Because of the focused ocean observations supporting the Deepwater Horizon spill mitigation, we also began a preliminary assessment of the Lagrangian predictive skill of Gulf of Mexico HYCOM model surface velocities by comparing evolving spill boundaries estimated from sequences of satellite imagery with predicted spill evolution from the model. Satellite imagery with spill boundary estimates were made available on the web by the Optical Oceanography Laboratory at the University of South Florida. We also identified a number of drifters deployed around the Deepwater Horizon site, which will be valuable for more quantitative assessments of a number of Navy GOM models that supported the spill effort.

WORK COMPLETED

The following tasks were completed during this performance period:

- Assessed the Lagrangian predictive skill of the Navy EAS16 model in the western Pacific using drifter trajectories from four Navy acoustic experiments during the period 2004 through 2007.

- Assessed the Lagrangian predictive skill of a 24-member Navy RELO model ensemble using 30 drifter trajectories from the LWAD-07 experiment in early October 2007.

- Completed a preliminary assessment of the Lagrangian predictive skill of the Gulf of Mexico HYCOM model during the Deepwater Horizon spill by comparing estimates of the evolving spill boundary from satellite imagery with model predictions.

- Computed LCS maps (as direct Lyapunov exponents) for GOM HYCOM surface velocities during the Deepwater Horizon spill period.

- As part of project *N00014-09-1-0703* (see below), adapted tools for normal mode analysis (developed with prior ONR support) to blend observed trajectories with model forecast velocities to improve trajectory forecasts.

- Completed comparisons of ten-day LWAD-07 observed trajectories with EAS16 model hindcasts and documented this analysis in a publication now under review.

RESULTS

Drifters from four separate Navy acoustic experiments provided independent trajectory observations for assessing the EAS16 model during the 2004-2007 period. Figure 1 shows a map of the western north Pacific Ocean and the geographic limits of all drifter trajectories for each of the four experiments. Table 1 shows the number of trajectories for each experiment and summarizes the Lagrangian predictive skill statistics. The limits of the standard deviation window were computed as the mean minus the negative one-sided standard deviation and the mean plus the positive one-sided standard deviation. One-sided standard deviations are appropriate for this metric, which is positive definite. Figure 2 shows histograms of separation after three days for each experiment. The mean value and the limits of the standard deviation window are also shown.

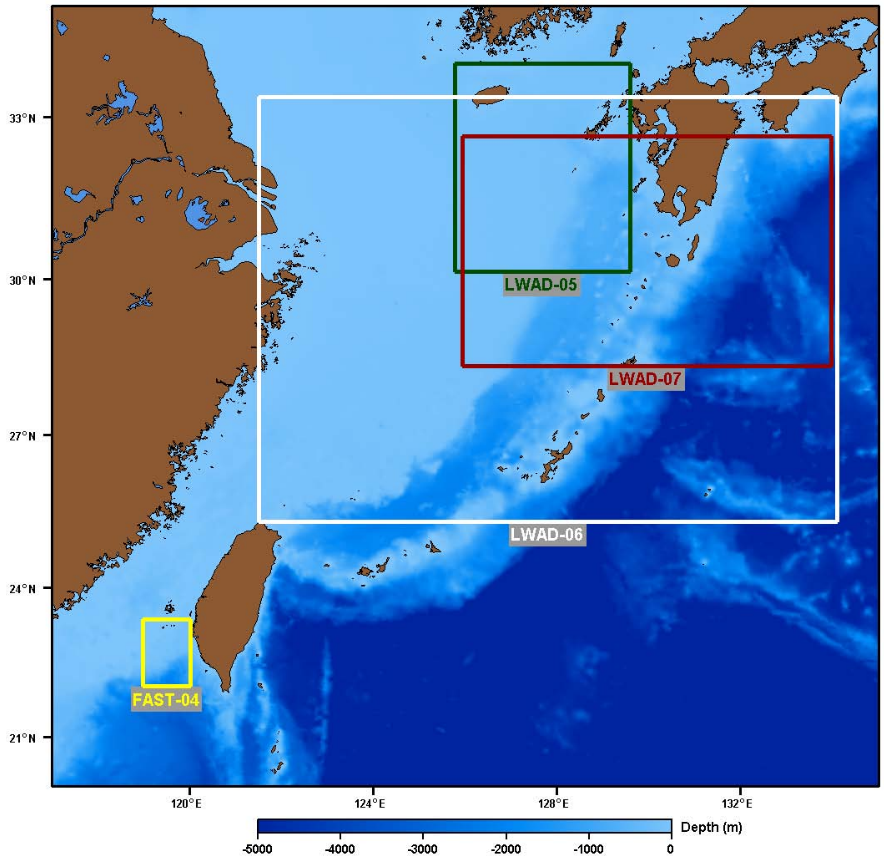

Figure 1: Map of the western north Pacific Ocean showing the geographic boundaries of four Navy acoustic experiments that included drifter launches during the period 2004 through 2007. Drifters launched during these experiments were used to assess Lagrangian forecasts from the Navy EAS16 model and ensemble Lagrangian forecasts from the Navy RELO model.

Table 1: Lagrangian skill assessment statistics for the EAS16 model (2004-2007)

	FAST-04	LWAD-05	LWAD-06	LWAD-07
Number of drifters	12	16	10	30
Number of trajectory segments	71	243	264	286
Mean separation after 3 days (km)	56.7	27.8	49.9	72.4
Standard deviation window	[31.5 79.6]	[14.2 46.2]	[26.0 100.4]	[31.0 136.3]

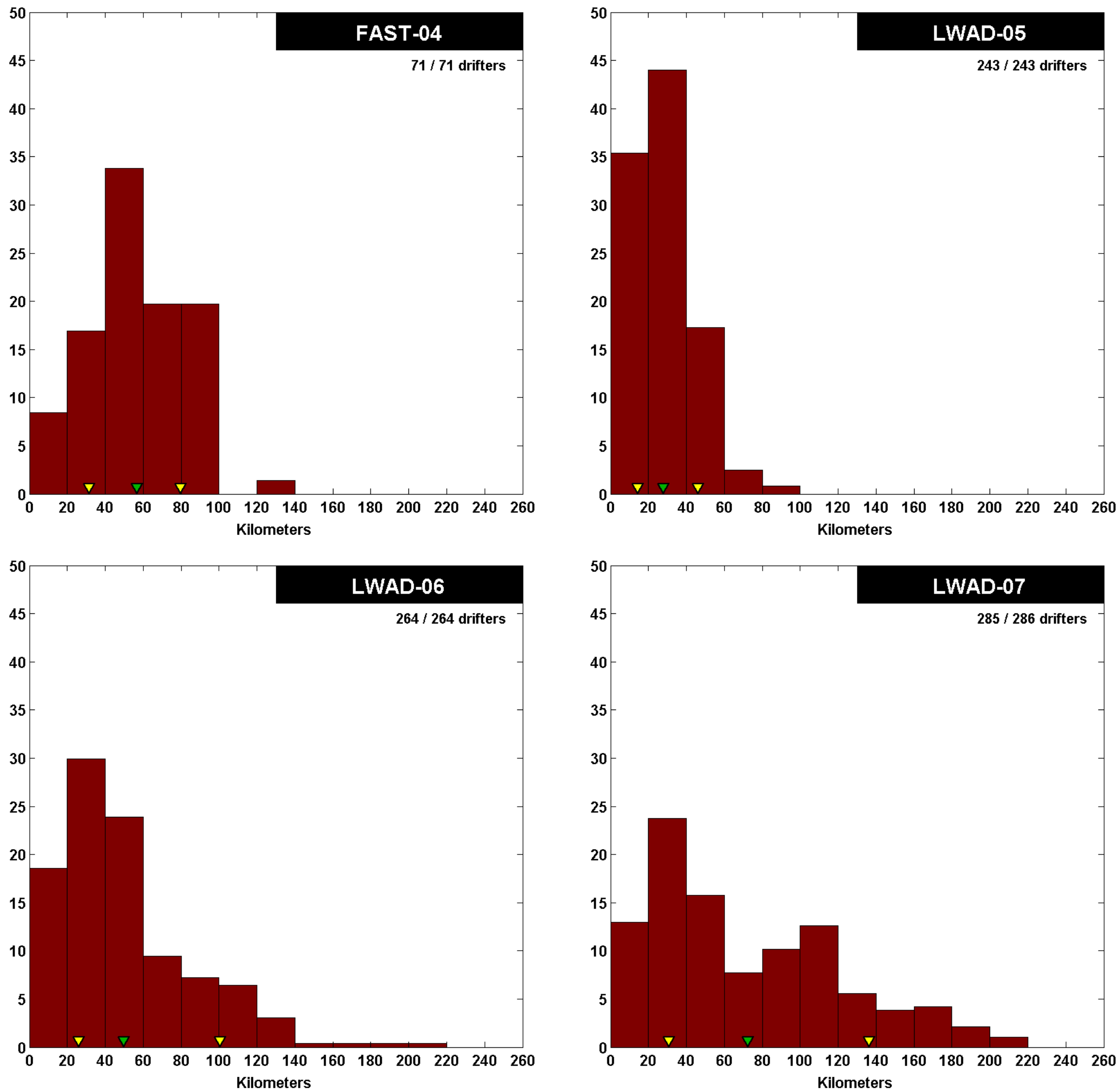

Figure 2: Distributions of separation (in km) between observed and modeled trajectories (from EAS16 model forecasts) after three days for drifters launched during four Navy acoustic experiments. Histogram counts (y-axis) have been normalized by the total number of trajectories analyzed for each experiment. Mean values are shown as green triangles. The limits of one standard deviation from the mean (computed as positive and negative, one-sided) are also shown, as yellow triangles.

Table 1 and Figure 2 show that separation after three days varies substantially among individual trajectories in a single experiment. Mean values also vary widely between the experiments, ranging from a minimum of 27.8 km (LWAD-05) to a maximum of 72.4 km (LWAD-07). Differences in the ocean circulation among the four experiment areas likely accounts for some of this variability. A detailed analysis of EAS16 Lagrangian predictive skill for the LWAD-07 experiment (Huntley *et al.*, 2010) based on ten-day trajectories suggests that model errors in the position of the Kuroshio may contribute to degraded forecast skill. That analysis also showed that forecast skill was insensitive to the removal of model tidal currents and to coarsening of the model velocity archive in both space and time by up to a factor of eight.

The Lagrangian predictive skill of a twenty-four member RELO ensemble was also assessed using 104 observed trajectory segments (“launched” at three day intervals) from the LWAD-07 experiment. Histograms show wide-ranging variability of three-day separation distributions among ensemble members, with mean values ranging from 60 to 80 km. Although the RELO model had twice the spatial resolution compared to EAS16 (3 km vs. ~7 km), it did not demonstrate any statistically significant improvement in Lagrangian predictive skill.

In May 2010, we gained access to surface velocity forecasts from the GOM HYCOM model, archived at three-hour intervals. We used these forecasts to compute LCS maps and study their evolving structure. The LCS maps showed a lot of small-scale structure around the Deepwater Horizon site, driven by a number of submesoscale eddies. We also conducted a preliminary Lagrangian assessment of the model by evaluating its ability to predict the evolution of the Deepwater Horizon surface oil slick boundary when compared with a sequence of two satellite images over a five-day period. Figure 3 (top) shows the estimated spill position (in green) at 1900 UT on 13 May 2010. The boundary of the spill, estimated by the USF group, was used to initialize a curve along which model trajectories were launched. Additional trajectories were re-seeded along the curve as needed to ensure the along-curve spacing remained within a specified limit. The model spill boundary was integrated over five days, and its final position compared with the satellite position estimate at 1900 UT on 18 May 2010 (Figure 3, bottom, in yellow).

Figure 3 shows that the model Loop Current was able to account for the elongation and entrainment of the spill to the southeast. However, the model advected most of the oil too far to the west and failed to capture a significant fraction of the spill that moved north, toward the Louisiana-Mississippi shelf. While these qualitative comparisons are suggestive, more quantitative comparisons with drifter trajectories are needed. Other important processes that influence an evolving oil slick, like evaporation, aging, action of dispersants, and wind effects, must also be considered. In addition, the accuracy of spill boundary estimates from satellite imagery in this region has not been thoroughly assessed.

IMPACT/APPLICATIONS

As part of a related project (*N00173-08-1-G009*, see below) we are exploring how Lagrangian analysis tools can be incorporated into Navy acoustic tactical decision aids. As the Navy user community for Lagrangian forecast products continues to grow, quantitative assessments of Lagrangian forecast skill become vital. Users need to know the expected accuracy of a forecast, as well as quantitative estimates of uncertainties.

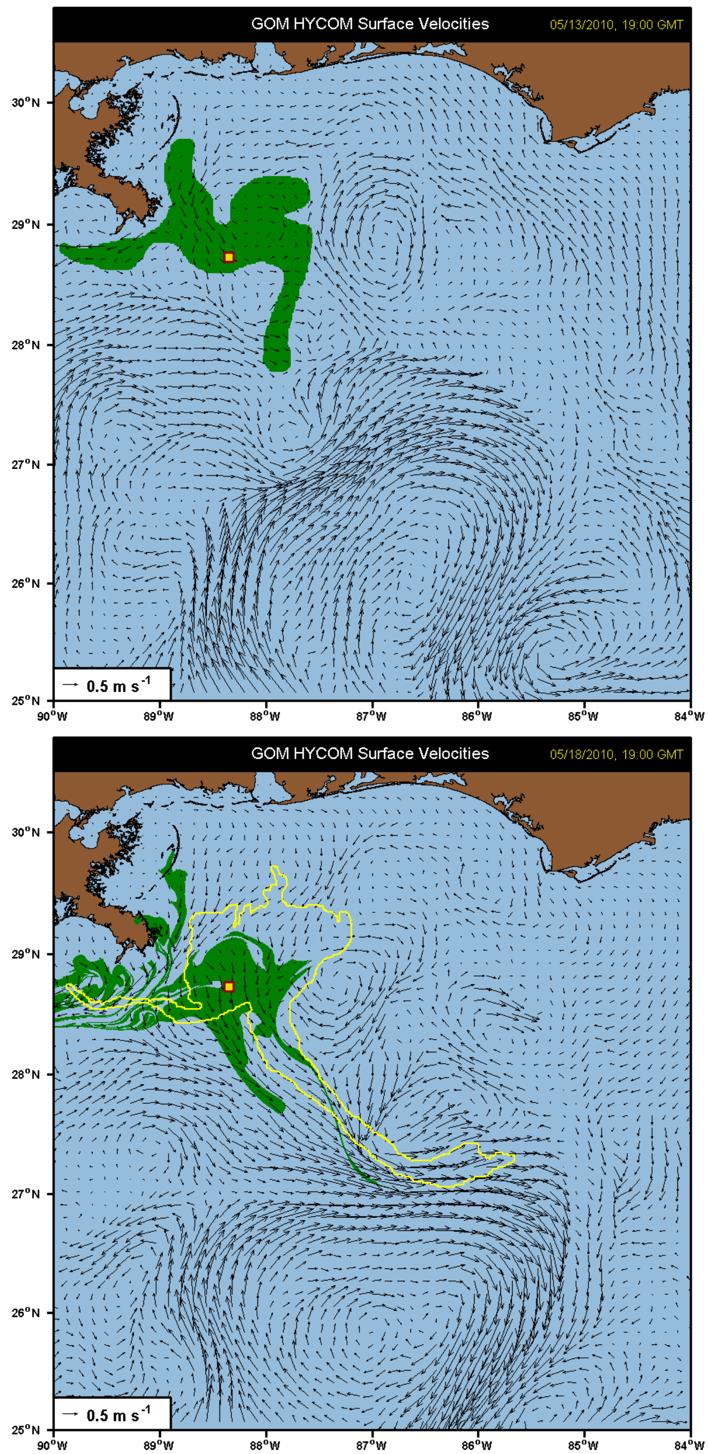

Figure 3: (top) Initial Deepwater Horizon oil spill position (in green) estimated from a satellite image on 1900 UT, 13 May 2010. (bottom) Spill position predicted by simple advection using GOM HYCOM model surface velocities (in green) at 1900 UT, 18 May 2010. The boundary of the spill at this time, estimated from an updated satellite image, is also shown (in yellow). In each panel, GOM HYCOM model surface velocity vectors are shown in black, and the Deepwater Horizon site is shown as a yellow square.

The Lagrangian skill assessments briefly described here are a first step toward quantifying uncertainties. Since forecast skill almost certainly depends on specific geographic regions and time periods, additional assessments with observed drifters in other ocean regions are needed. Exploring the range of model uncertainty through ensembles will also prove valuable.

RELATED PROJECTS

The investigators for this effort, along with Dr. Helga Huntley, are also investigators on five other closely-related ONR efforts:

N00014-11-1-0087: Dynamical systems theory in 4D geophysical fluid dynamics – This newly funded MURI effort involves a large group of investigators at several institutions focused on extending Lagrangian analysis of general circulation models to three spatial dimensions.

N00014-10-1-0522: Lagrangian transport signatures in models and observations – This work focuses on identifying circulation features like fronts and eddies in satellite imagery and comparing the evolution of these features with ocean model forecasts as a model assessment tool.

N00014-09-1-0703: How well do blended velocity fields improve the predictions of drifting sensor tracks? – In collaboration with a group at RSMAS, this project explores two different methods of data blending and their effectiveness for improving trajectory predictions. Since trajectory predictions underlie all other Lagrangian analyses, enhancing their accuracy is immediately relevant for all applications of Lagrangian forecasts.

N00173-08-1-G009: Prediction of evolving acoustic sensor arrays – This effort is focused on demonstrating how Lagrangian analysis of Navy ocean model predictions can be performed at a Navy operational center and how Lagrangian products can be delivered to fleet operators on scene in near-real time to support tactical decision making.

N00014-07-1-0730: Enhanced ocean predictability through optimal observing strategies – This effort strives to apply synoptic Lagrangian tools to a regional ocean model off the coast of northern California as a proof of concept exercise demonstrating how knowledge of the evolving ocean might aid fleet operators concerned with optimizing AUV deployments in the coastal ocean.

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